PARAMETRIC ESTIMATION OF U-TURN VEHICLES AT MEDIAN OPENINGS IN URBAN INDIAN CONTEXT

A Thesis

Submitted in partial fulfilment of the requirements

for the degree of

Master of Technology

In

Transportation Engineering

PANNELA SATISH KUMAR

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DEPARMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA-769008, 2015

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Under the guidance of

Prof. (Dr.) Prasanta Kumar Bhuyan

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NIT Rourkela

CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled **"PARAMETRIC ESTIMATION OF U-TURN VEHICLES AT MEDIAN OPENINGS IN URBAN INDIAN CONTEXT"** in partial fulfilment of the requirements for the award of **Master of Technology** Degree in **Transportation Engineering** submitted in the department of **Civil Engineering** at **National Institute of Technology, Rourkela** is an authentic record of my own work carried out under the supervision of **Dr. Prasanta Kumar Bhuyan**, Assistant Professor, Civil Department.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other national or international level institute/university.

(Pannela Satish Kumar)

This is to certify that the above statements made by the candidate are correct and true to best of my knowledge.

(Dr. Prasanta Kumar Bhuyan)
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This thesis is dedicated

To

my beloved Father and Mother,

May God bless them and elongate them live in his obedience.

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ABSTRACT

The purpose of capacity modelling at U-turns is to develop a relationship between capacity and and its geometric characteristics. In fact, the few models available for the estimation of capacity at different transportation facilities does not provide specific guidelines at median openings. For this reason, an effort is made to estimate the capacity by collecting the data sets from median openings at different lane roads of Hyderabad City, India. Wide difference (43% -59%) among the capacity values estimated by the existing models shows the limitation to consider for the mixed traffic situations. Thus, a new model is proposed for the estimation of the capacity of U-turn vehicles at median openings considering mixed traffic conditions which would further prompt to investigate the effect of different factors that might affect the capacity. In order to estimate the critical gap of U-turn vehicles, recently developed method 'INAFOGA' which is based on clearing behavior of drivers at un-signalized intersections is modified and applied considering the merging behaviour of U-turn vehicles at median openings and named as 'Modified INAFOGA' method. Modified INAFOGA method is compared with probability equilibrium method through paired-sample hypothesis (t-test) and result revealed that difference in mean values 0.009 signifies that both methods are comparable. Difference in critical gap values obtained from the box plots and radar charts indicates that Probability equilibrium method is not suitable to address the behavior of U-turn vehicles at median openings under mixed traffic conditions and these observations validates the fact that 'modified INAFOGA' method is indeed appropriate under mixed traffic conditions. Follow up time is estimated by measuring the time gap between two successive U-turn vehicles which are being queued to take a U-turn. The estimation of capacity model proposed in this paper is simple, easy to implement and suitable to mixed traffic conditions.

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CHAPTER 1

INTRODUCTION

1.1 Background

The main purpose of capacity modelling of U-turn median opening is to develop useful relationships between capacity and set of traffic and geometric characteristics. The developed model should be easy for practical applications and predictive under different traffic conditions. It should be noted that median openings are provided to facilitate traffic turning movements. As part of traffic management system in order to improve intersection operation, some illegal movements are not permitted at intersection locations, especially along divided arterial. In most of the cases, such minor movements are accommodated at separate U-turn median openings. Compared with turning movements at intersections, U-turn movement at median openings is highly risky and complex. Generally, the speed of through traffic stream is relatively high and the turning vehicle must wait for accepted gap and then turn under low speed level. Therefore, the turning vehicle needs large gap in the conflicting stream before performing the U-turn. In fact, the few studies which contain procedures and models for estimating capacity for different movements at un-signalized intersections do not provide specific guidelines for estimating capacity of U-turn movement at median openings in urban Indian context. For this reason, an effort was made to estimate the capacity of U-turn vehicles at median openings. Although the U-turn movement is more complex than right-or left-turning movements at un-signalized intersections, the general concept and procedure proposed for analyzing capacity at median openings is very crucial in this respect. Capacity of median openings mainly depends on critical gap and follow-up time of U-turn vehicles. Hence a thorough investigation on gap acceptance behavior of U-turn vehicles is carried out in this study.

Gap is defined as the time or space headway between two successive vehicles in the through traffic stream (Solberg and Oppenlander 1964; Uber, 1994) [1-2]. Gap differs from headway in the fact that the former as the time length between back bumpers/wheel bases and the latter is measured as time span between front bumpers of two successive vehicles. “Gap acceptance” analysis forms the prime objective for safe operation of U-turning vehicles at median openings under heterogeneous traffic situations. Critical gap is an essential parameter used in the study of gap acceptance. Critical gap is defined as the size of the gap whose number of accepted gaps shorter than equal to the number of rejected gaps longer than it (Hewitt, 1983) [3]. HCM (1994, 2000) modified the critical gap as the minimum time interval in the major stream traffic that allows intersection entry of one minor-street vehicle [4]. Regarding the above definition "Critical Gap" for U-turns at median openings is "the minimum time interval in between two through/conflicting traffic vehicles that allows complete merging movement for one U-turn vehicle at a median opening". Gaps that are smaller than the critical gap usually are rejected, and all gaps larger than this critical gap are expected to be accepted.

Estimation of critical gap under mixed traffic conditions in India is much more complicated than that under homogeneous traffic situations. Out of total around 20 percentages of vehicles are two wheelers which often get into any offered gap between bigger size vehicles and pass the median opening in an unsystematic way in Hyderabad city. The U-turn vehicles accept smaller gaps and force the through traffic vehicles to slow down and takes appropriate gaps for their movement. This forced gap acceptance affects the entry capacity of U-turn vehicles and causes delay to the through traffic stream. The joint effect of all these issues leads to the critical gap estimation a more difficult task under mixed traffic flow conditions. These situations need an additional look into the conflict area & critical gap concept near median openings. In heterogeneous traffic conditions a lot of conflicting movements and illegal lane changing operations result in accidents and congestion at the median opening sections. Gap acceptance analysis in lieu of median openings under varying road geometrics coupled with heterogeneous conditions has not been given proper consideration. The traffic engineering manual HCM, even in its recent issue of 2010 had not addressed the gap acceptance behaviour of driver for median openings.

In this paper, an intrepid effort has been taken to estimate the capacity of U-turn vehicles prevailing on the median openings in India, which would further prompt to investigate the effect of different relevant factors that might affect the estimated capacity under mixed traffic conditions. In this report, video data have been collected from the Hyderabad city located in the southern part of India. Gap acceptance and estimation of capacity under mixed traffic is extremely difficult to evaluate and corroborate. Thus, the merging concept has been developed from the "INAFOGA" method to estimate the critical gap of U-turn vehicles. It has been observed from the results that "INAFOGA" method is indeed more appropriate than Probability Equilibrium method in addressing the mixed traffic situations in India. A new model is proposed to estimate the capacity of U-turn vehicles at median openings which is best suitable under mixed traffic conditions.

1.2 Problem Statement and Motivation of the Work

1.2.1 Problems due to mixed traffic situations in India:

The traffic in India is exceedingly heterogeneous comprising of an assortment of quick moving vehicles such as car, bus, truck, scooter(motorized two-wheeler), auto rickshaw (motorized three-wheeler)and slow moving vehicle such as bicycle and pedal rickshaw. The static and dynamic aspects of these vehicles change altogether. In the absence of lane discipline and wide variation in sizes of different types of vehicles, vehicles willing to take U-turns are found to queue back to back near the median openings. Smaller size vehicles often squeeze through any available gap between large size vehicles and move into the median opening area in haphazard manner. The rule of priority is frequently disregarded and the U-turn stream vehicles enter the median opening area even in smaller gaps forcing the through/conflicting traffic stream to slow down and provide sufficient gaps for their movement. It changes the behavior of through traffic vehicles altogether and the gaps offered to the U-turn vehicles are not the natural time headway, but the modified ones. This forced gap acceptance which happens because of non- adherence to necessity, significantly affects the entry capacity of the lower priority stream and causes substantial delay to higher priority movements. It makes gap acceptance an extremely unpredictable phenomenon. All these situations require a re-look into the concept of critical gap, conflict area at the median opening and method of data extraction.

1.2.2 Motivation of Work

The problems faced by U-turn drivers at the selected median opening sites motivated the researchers to develop a concept of merging behaviour of U-turn drivers at median openings which would in a broad extent help future traffic engineers in analysing the capacity of U-turn vehicles at median openings. As because critical gap is the sole parameter for estimation of capacity U-turns, which cannot be directly measured standing at the site or the field in consideration. Existing methodologies like Raff, Harders, and probability equilibrium methods has been used under homogeneous traffic conditions. This study focuses on utilising the above methods under heterogeneity of Indian traffic. There is an urgent need for comparison of the above methods with the “INAFOGA” method for U-turning mixed traffic in India. Thus, comparisons and significance tests are shown to validate the above statement. Estimation of capacity of U-turn vehicles at median openings also explained in this study by proposing a model which can consider mixed traffic conditions.

1.3 Research Objectives

Based on the above mentioned problems, following are the tentative research objectives:

- Estimation and comparison of critical gap through existing methodologies and models present at a median opening for U-turns under mixed traffic conditions.
- Estimation of follow up time for U-turn vehicles.
- The main aim of the research is to estimate capacity of U-turns at median openings under mixed traffic conditions.

CHAPTER 2

REVIEW OF LITERATURES

Majority of the literatures are available for the estimation of critical gap and follow-up time at different transportation facilities such as rotaries, un-signalized intersections and median openings. However, limited research has been carried out to estimate the capacity of U-turn vehicles at median openings and described in the following sections.

2.1 Critical gap

Many researchers have worked on the concept of gap acceptance during the past few years, but most of them considered homogeneous traffic flow situations. According to available literatures, several techniques or models have been established since the year of 1947 for the estimation of critical gap as clearly as possible [5-9]. Thus, it is clear that literatures regarding gap acceptance phenomenon are rich. The majority of literatures normally considers the rejected and accepted gaps as the key parameters for the critical gap estimation. "HCM 2010" states that critical headway/gap can be estimated on the basis of observations of the largest rejected and smallest accepted gap corresponding to a given transportation facility (HCM, 2010) [10].

Raff and Hart (1950) first proposed the term "critical lag" as an important parameter in the determination of gap acceptance for a minor street driver willing to take a directional movement in an un-signalized intersection. Also the author proposed a graphical model in which two cumulative distribution curves related to the number of accepted and rejected gaps intersect to yield the value of critical Lag [11]. Miller (1972) corrected the Raff's model and concluded that the developed model is suitable for light-to-medium traffic but is not acceptable for heavy traffic conditions. The author also verified that the model gives satisfactory results for gaps as that obtained for lags. Further the author suggested a gap acceptance model to check the applicability of various methods for the estimation of critical gap. Simulation was used to create artificial data and similarity was checked based on the median value predicted by each method. Results observed by the authors shown that the application of maximum likelihood technique exhibited satisfactory results for the critical gap estimation [12]. Troutbeck (1992) gave a more precise form of maximum likelihood method with a satisfactory mathematical derivation for the same purpose and suggested that the maximum likelihood method is most useful and accurate method in calculating the gap acceptance particularly when minor stream traffic is low [13]. Brilon et al. (1999) compared several methods such as Raff, Ashworth, Hewitt, Harder and Maximum likelihood procedures for the critical gap estimation using simulation and concluded that best method should be selected based on the observation and not solely depending on the major street traffic volume [14]. Yang, X.K., et al (2001) estimated the critical gap value of U-turn vehicles at median openings using Logit model and Raff's method. The authors concluded that the critical gap value of U-turn vehicles at median openings varied with respect to traffic and geometric conditions and the distributions of the U-turn gaps shown that the behavior of driver significantly affect the U-turn gaps [15]. Ning Wu (2012) presented new model based on the equilibrium of probabilities for accepted and rejected gaps for critical gap estimation at un-signalized intersections. Regression analysis was used to calibrate the distribution functions of critical gaps and observed that Weibull distribution was better fitted than log normal distribution for the conditions [16-17]. Obaidat et al. (2013) estimated length of time gap needed by a U-turn driver to cross the median opening based on factors such as driver's age and gender and the study describes the effect of driver-related factors on gap acceptance [18].

For heterogeneous traffic flow conditions, Ashalatha et al. (2011) used existing methods like Probit, Hewitt, modified Raff, Logit and Harder methods for estimation of critical gap at an un-signalized intersection. There was a wide difference (12-38%) between the critical gap values which highlighted the limitation of the methods to address mixed traffic situations [19-20]. Thus, the authors came up with an alternate technique making use of the clearing behavior of drivers in conjunction with gap acceptance data. The new method proposed in this study was simple and easy to implement under Indian conditions. With due consideration, this paper has given significant background for the present study because of its heftiness towards mixed traffic conditions prevailing in India. The "clearing behavior" assumed for un-signalized intersections in the previous study was improved to "merging behavior" in case of U-turn vehicles at median openings in this study. It considers the actual merging behavior in addition to the gap acceptance features of a vehicle. Merging time shows the manner in which a movement is implemented at a median opening. It alternatively takes into account the difficulties found under mixed traffic conditions.

2.2 Follow up time

Follow up time is defined as the average time gap between two successive U-turn vehicles that are being queued and entering the through/conflicting stream gap one behind the other. Thus, the follow up time is defined as the headway that states the saturation flow rate for the U-turn movement if there are no through traffic vehicles on high priority movement. Different methods are available for estimating follow-up time. In HCM, follow up time was directly estimated in the field by measuring the time gap between two successive vehicles taking the same gap in the through traffic stream.

2.3 Capacity of U-turn vehicles

In the previous study concerning the capacity of U-turn vehicles at median openings, Al-masaeid (1999) suggested a linear regression model for capacity estimation of U-turn vehicles at median openings and to explore the effect of different features that might affect the capacity estimation. The author also calculated the follow-up time and critical gap of U turn vehicles to calculate the capacity of U-turn movement based on the gap acceptance model suggested by HCM (1994). Further, the author compared the linear regression model with the results of gap acceptance model and concluded that the gap acceptance model provided by HCM (1994) suggested reasonable capacity estimation for U-turn movements. However, the author did not explain the methods that are used for the estimation of the critical gap and follow-up time for U turns [21]. In HCM (2000), the potential capacity of a particular minor movement is estimated by a gap acceptance model which was developed by Harder's (1968)[4]. Aldian et. al. (2001) observed the applicability of some traffic models to determine the capacity of U-turn vehicles at median openings. The modified random platoon Tanner's formula was found to be the most appropriate model. The results further indicated that this model could be used to determine capacity of any priority controlled intersection where platooning occurs in conflicting stream. Full knowledge about the headway distribution of major traffic is very important in selecting a model to determine priority junction capacity [22]. Liu et. al. (2007, 2008a, 2008b, 2009) have conducted a detailed research relating to capacity estimation of U-turn vehicles at median opening. The author estimated the parameters (critical headway and follow-up headway) of U-turn movements from the field data and validated the capacity estimation from the model with the field capacity. The model provides reasonable estimated capacity for U-turn movement at median openings. But the disadvantage of this model is that the author did not consider mixed traffic conditions and developed a model only on 4-lane roads [23-24]. Mohammed, H.K. (2008) used both empirical and simulation approaches to estimate the capacity of U-turn movement at median openings of divided arterial. The empirical approach using regression analysis was adopted to estimate the best form of the predictive equation for the U-turn capacity and investigate the effect of different relevant factors that might affect the estimated capacity. Simulation approach was used also to calculate capacity on the basis of the U-SIM model. This model represents the traffic performance at U-turn median openings and calculates the number of turning vehicles with respect to a different conflicting traffic stream. The results of both approaches were compared and presented in this study. A linear model was also recommended as a relationship between the average total delay of the U-turning vehicles and the conflicting traffic flow [25]. Jenjiwattanakul, T. et. al. (2013) evaluated the gap acceptance capacity model and proposed an adjustment method by v/c balancing ratio. The results showed that the gap acceptance capacity overestimated the field capacity in case of negative exponential headway distribution and underestimated in case of Erlang-2 headway distribution. The proposed adjustment could provide the estimated capacity closer to the measured field capacity. The method also incorporated the interactions between the U-turn and through traffic streams [26].

A critical review of available literatures indicates that few studies were employed to observe the capacity of U-turn vehicles during the past few years, but most of them considered homogeneous traffic flow situations. Therefore a new model is proposed for capacity estimation of U-turn vehicles at median openings considering mixed traffic conditions.

CHAPTER 3

STUDY METHODOLOGY

3.1 Estimation of Critical Gap

The critical gap t_c can be defined as the minimum time interval between the through traffic stream vehicles that is necessary for U-turning vehicle to make a merging maneuver. Values of critical gaps are different for different drivers (some of them are too fast or risky, some of them are slow or careful) and there are dependent on types of movements, geometry parameters of median openings, traffic situation. Due to this variability gap acceptance process is consider as a stochastic process and the critical gaps are random variables. The estimation of critical gaps tries to figure out qualities for the variables and also for the parameters of their distributions, which speak to normal driver conduct at the investigated openings. The problem is that the critical gaps cannot be measured directly. Only rejected gaps and accepted gaps of each U- turning vehicle can be measured at the Median Opening. The critical gaps can be estimated from these input data using some statistical method or procedures. For the estimation of critical gaps from the field data extracted, four different methods which will be used for analysis and comparison are described in this Chapter of the Report – Modified raff method (1950), Harder's method (1968), and Macroscopic probability equilibrium method of Ning Wu (2006) and "Modified INAFOGA" method.

3.1.1 Models/Methods Used For Estimation of Critical Gaps

3.1.1 Modified INAFOGA method

Highly heterogeneous traffic flow on urban Indian roads with no proper lane discipline form median openings a complex location for researchers to come up with a concrete idea on gap acceptance behavior of drivers. Although the informatory signs are provided prior to median openings, the U-turn vehicles move to some distance inside the influence area beyond the desirable. So, the reference point for a U-turn vehicle taking a gap in the through traffic must be explained here. The U-turn vehicles were observed to move about half of the influence area. So the thick line as shown in Fig. 3.5 is indicated as the stop line and this is the reference line for the coming of U-turn vehicles. Generally the gaps in the through traffic stream are measured at the single arrow line shown in Fig. 3.5 gives the headway distributions when through traffic stream is not obstructed.

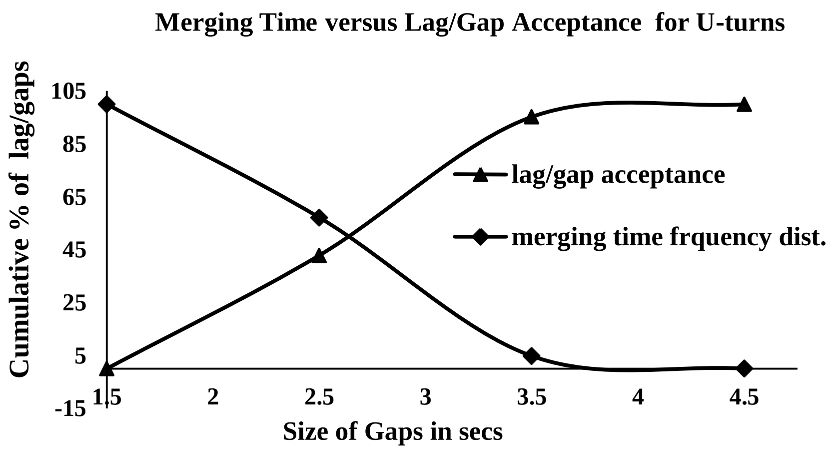

Fig. 3.6 Illustration of Critical gap estimation by Modified INAFOGA method

3.2 Estimation of Follow up time (t_f)

Follow up time can be directly measured in the field. Follow up time (t_f) is the average time gap between two successive U-turn vehicles being queued and entering the through/conflicting stream gap one behind the other. Follow-up time can be measured for individual vehicles whenever two consecutive vehicles in a queue discharge from a minor stream.

3.3 Estimation of Capacity

The primary purpose of capacity modeling is to develop a useful relationship between the capacity of U-turn vehicles at median opening and a set of traffic and geometric characteristics. The developed model should be easy for practical applications and predictive under different traffic conditions. Generally from the available models, the capacity of U-turn vehicles at median openings is affected by a number of factors. These factors include, (1) through traffic volume in the direction that is in conflict with the U-turning vehicles (2) the critical gap for U-turn movement and (3) the follow-up time for U-turn movement.

CHAPTER-4

STUDY AREA AND DATA COLLECTION

4.1 Area of study

Hyderabad City is considered in such a fashion that the road networks give the required input data for analyzing "Critical Gap" and comparing the same between different modes of transport. Median openings at four-lane, six-lane and eight lane divided urban roads are considered in the present study. In this context, it has been observed that median openings are generally provided in urban areas on major streets for minimum flow of 500 vehicles/day with a maximum speed limit of 70-80 km/h.

The data were collected from six sites of the Hyderabad city located in the southern part of India. To represent mixed traffic conditions in India, various motorized modes such as two wheelers (2W), three wheelers (3W), four wheelers (4W), different models of sports utility vehicles (SUVs), are taken into consideration and heavy vehicles like busses, trucks and multi-axle vehicles are ignored. It is observed that, the percentage of vehicles make U-turn at median openings is proportionately high as the distance of the openings from signalized/un-signalized intersections increases. Considering this fact, median openings roughly spaced at about 120-165 meters from their nearest intersections or rotaries are observed in this research. All the median openings are nearly similar in geometry with two, three or four lanes each on either side of the medians. The speed limit displayed on the roadsides for the conflicting or through traffic varies from 35-55 km/h for different mode of transportation. Fig. 4.1 gives the clear idea on U-turn vehicles and through traffic vehicles considered in this study.

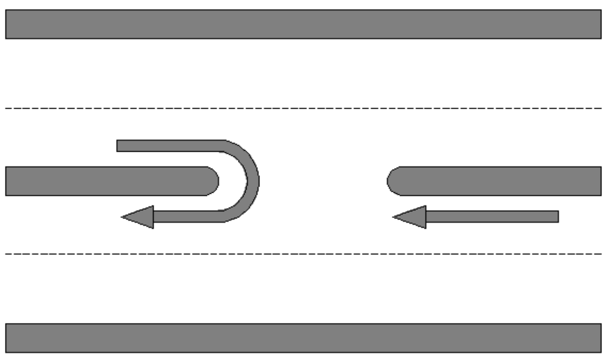

Fig. 4.1 Typical layout of U-turn median openings

4.2 Details of Traffic Video Data Collected

Data collection primarily composed of video recording of the selected median openings. Videos were recorded during morning and evening peak hours between October 2014 and January 2015. Traffic volume data was extracted from these video recordings in the office.

4.3 Geometric feature details of road sections

Apart from these data collection, geometric feature details of road sections are also collected. All the median openings are similar in geometry with two, three or four lanes on each side. The layout of the typical median opening is shown in Fig. 4.2 and its geometric feature details are shown in Table 4.1

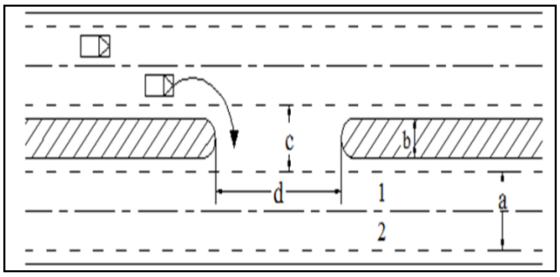

Fig. 4.2 Layout of typical median openings on a four-lane road

Where,

a= distance between inner lanes

b= width of median

c= distance between outer edge of inner lanes

d= horizontal width of median opening.

Table 4.1 Geometric feature details of road sections

Section Number	Geometry of median opening (m)			
	a	b	c	d
1	14	2.5	3.3	14.72
2	11	2.4	3.2	13.8
3	13.8	2.5	3.4	14.5
4	7.5	1.6	2.1	20
5	10.8	2.4	3.2	20.3
6	7.2	1.4	2.1	15.7

4.4 Summary of the Chapter

The area of study can be broadly classified based on the necessity of data for analysis of Critical gap and comparison of different modes of transport. There were three types of median openings mainly prevailing in INDIA. First one being on a typical 4-lane divided highway, second one on a 6-lane divided street and the third one on a 8-lane divided highway. Median openings are provided in urban areas for minimum major street flow of 500 vehicles/day having a maximum speed limit of 70-80 kmph (40 miles/hr.). Hyderabad being the capital of Telangana consists of a large road network on which mixed traffic is dominant. Modes like four-stroke Autos, Light commercial vehicles like Tempos and Pick-up vans, Categories of cars comprising of Sedans and Hatchbacks along with other Sports utility vehicles make a wholesome of 600-500 vehicles per day on most of the U-turns prevail within the city’s domain. Each median opening were approximately spaced about 600-700 feet distance from their near unsignalized intersections as stipulated by HCM 2010. However, in some of the median openings inconsistency of drivers taking U-turns were noted but irrelative data pointe were neglected for finding critical gap values.

CHAPTER-5

ANALYSIS & RESULTS

5.1 Estimation of Critical Gaps by Different Methods Used

5.1.1 Modified INAFOGA method

After the video recording of the median openings, extraction of necessary decision variables for the estimation of critical gap is done. All decision variables are extracted by playing the .AVI videos in demuxer software named as AVIDEMUX Version 2.6 capable of running videos at a frame rate of 25 frames/second. The time frames chosen for data extractions are based on the new concept on merging time are explained below. Fig. 5.1 represents the schematic representation of all these time frames.

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Fig. 5.1 Schematic representation of time frames used in data extraction

Lag is calculated as the time gap between appearance of a U-turn vehicle on median opening and appearance of first through traffic vehicle at the U/S end of INAFOGA (single arrow line). If the lag is rejected then the difference between the appearances of successive through traffic vehicles at the U/S end of INAFOGA is taken as gap. Lag acceptance will be relatively high under the mixed traffic situations where there are a large number of smaller size vehicles. Ignoring the lag acceptance data will be probably wasteful. Therefore, in the present study no difference is made between the gap and the lag.

Here the lag may be rejected or accepted by U-turn vehicle. In the lag is rejected, gap is considered. Again, the gap may also be rejected or accepted by the U-turn vehicle. It is absolutely continued until a gap was ultimately accepted by the U-turn vehicle. Therefore the U-turn vehicle will probably be searching for a gap in the through traffic to take a suitable turn.

Table 5.1 Basic Statistics of the Data collected from all sections

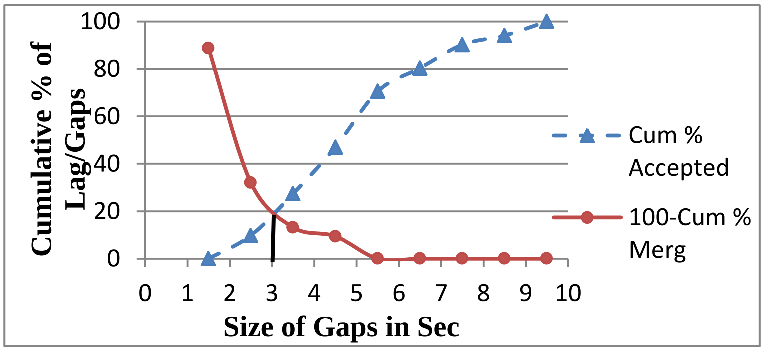
Vehicle Type	Limits	Accepted Gaps (s)	Rejected Gaps (s)	All Gaps (s)	Merging times (s)
For 4W	Minimum	0.413	0.069	0.069	0.827
	Maximum	9.931	8.518	9.931	7.448
For 3W	Minimum	0.142	0.138	0.138	1.241
	Maximum	12.414	4.966	12.414	12
For 2W	Minimum	0.413	0.241	0.241	0.276
	Maximum	11.179	5.794	11.179	6.621
For SUV	Minimum	0.827	0.069	0.069	1.242
	Maximum	21.276	5.793	21.276	10.344

Accepted gaps and rejected gaps data were calculated for different modes of vehicles from all sections and merging times for all sections were calculated by merging behaviour concept for critical gap estimation. Table 5.2 represents the total number of accepted gaps, rejected gaps and merging times along with total number of vehicles detected in this study.

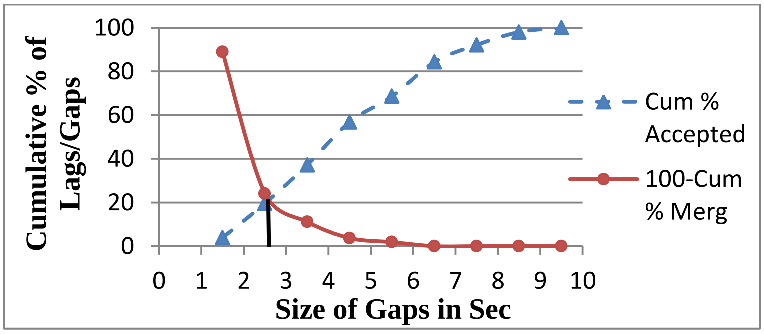
Table 5.2 Total number of observed gaps for all the sections

Vehicle Type	Total no of Accepted Gaps	Total no of Rejected Gaps	Total no of Merging times	Total no of vehicles detected
4W	242	460	242	242
3W	272	344	272	272
2W	296	366	296	296
SUV	234	370	234	234

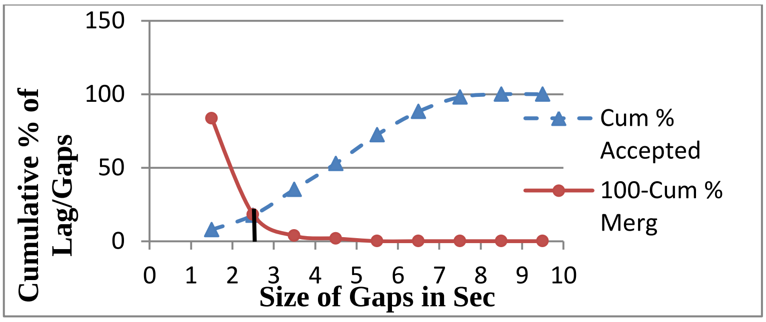
Both accepted lags and gaps are used in this method to determine critical gaps. Cumulative frequency percentages of lags and gaps are plotted against merging time expressed as frequency distribution. The intersection point of these two curves further projected on the X-axis represents the critical gap value. Fig. 5.2 represents the critical gap of U-turning 4wheelers, 3wheelers, 2wheelers and SUVs for section 1 using modified INAFOGA method. The remaining five sections follow the same pattern of plot.



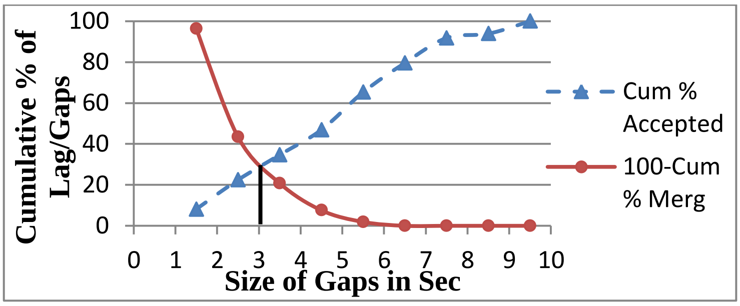
(a): Critical gap estimation for 4W



(b): Critical gap estimation for 3W



(c): Critical gap estimation for 2W



(d): Critical gap estimation for SUV's

Fig. 5.2 Critical gap estimation by modified INAFOGA method for 4W, 3W, 2W and SUV's

Mode wise critical gap values for all median openings are shown in Table 5.3 by existing methods.

Table 5.3 Critical Gap Values by Existing Methods

Median Opening Section no.	Vehicle Type	modified INAFOGA method (s)	Probability equilibrium method (s)	modified Raff method (s)	Harder's method (s)
Section 1	4W	3	2.9	3.5	5.25
	3W	2.6	2.5	3.15	5.25
	2W	2.5	2.4	2.75	4.75
	SUV	3	2.9	3.85	4.75
Section 2	4W	2.65	2.9	3.3	4.25
	3W	2.7	2	3.1	3.75
	2W	2.4	2.5	2.4	3.75
	SUV	4.8	3.1	4.8	5.75
Section 3	4W	3.2	2.25	3.5	4.25
	3W	2.4	1.9	2.9	4.25

	2W	1.8	1.5	2.4	3.75
	SUV	3.7	2.5	3.9	4.75
Section 4	4W	2.95	2.85	3.6	4.25
	3W	2.9	2.6	3.15	3.75
	2W	2.4	2.2	2.75	3.25
	SUV	3.25	2.9	3.15	4.25
Section 5	4W	2.85	3.45	4.8	5.75
	3W	3	2.6	3.45	4.25
	2W	3.2	2.85	3.7	4.75
	SUV	3.55	2.45	4.15	5.25
Section 6	4W	3.25	4.25	4.7	5.25
	3W	3.25	2.7	3.65	4.25
	2W	3.15	2.75	3.8	4.75
	SUV	3.65	3.4	4.1	5.25

5.2 Comparison of critical gap values by different methods used

Critical gap values obtained by modified INAFOGA method are compared with probability equilibrium method only such that this equilibrium method established macroscopically from the cumulative distributions of the accepted and rejected gaps.

5.2.1 Paired sample T-test

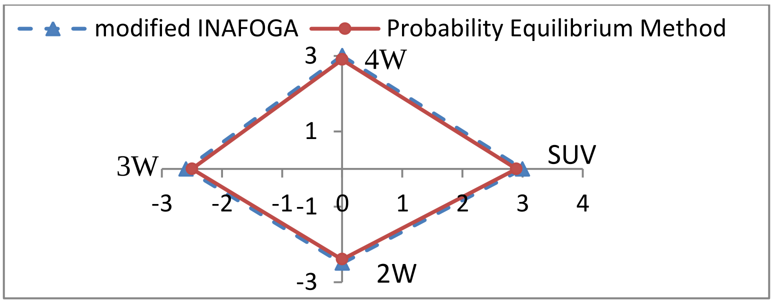
A paired sample t-test is conducted for the values of critical gap obtained by these methods as shown in Table 5.4 revealed that difference in mean values i.e. 0.009, which in turn lower than the two tailed minimum significance value (p = 0.05), signifies that modified INAFOGA method is comparable with Probability equilibrium method. The T- statistics value (2.830) justifies the significance of comparison between the two methods.

Pair	Paired Differences					Sample Size (N)	T-statistics	Degrees of Freedom (D.f)	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference					
				Lower	Upper				

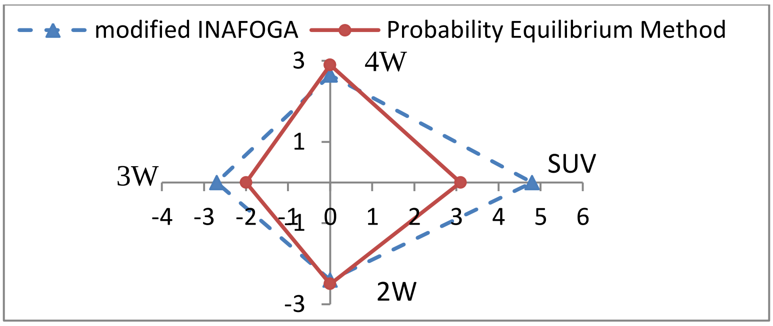
5.2.3 Radar charts

In an intention to plot critical gap values of four modes of vehicles considered in this study over these two methods, radar charts are drawn for the six sections as shown in the Fig. 5.7 Triangle and circular rings in the radar charts (Fig. 5.7) shows the spread of critical gap values for U-turns by modified INAFOGA and Probability equilibrium method. Four corners of the tetrahedral rings mark the four motorized modes and show their variation over the two methods used for comparison. With reference to the Radar charts as shown in Fig. 5.7, for section 2, section 5 and section 6 critical gap for Probability equilibrium method is higher than those obtained by modified INAFOGA method {(Section 2:2.9 s>2.65 s); (Section 5:3.45 s > 2.85 s); (Section 6: 4.25 s > 3.25 s)}.

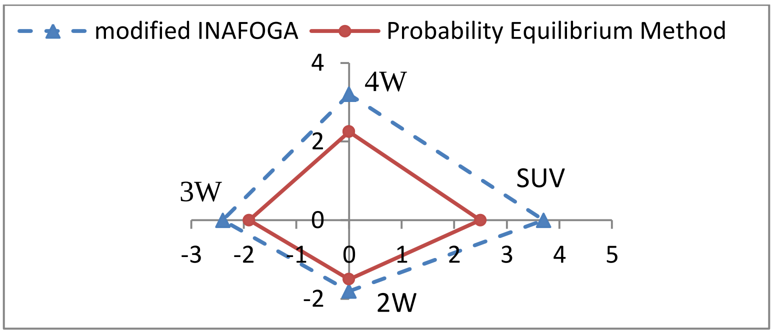
The radar charts shown in Fig. 5.7, section 1, 3, 4 are giving the rhombus like appearance while in the section 2, 5, 6 the 2 lines are overlapping each other resulting into the absence of rhombus like appearance. This observation on radar charts shows the inconsistency of critical gap values estimated by Probability equilibrium method over the modified INAFOGA method. Therefore, Probability equilibrium method is not suitable to address the behavior of U-turn vehicles under Indian mixed traffic conditions. However Box plots, Radar charts and T-Statistic Two tailed significance value coupled with higher critical gap values validates the fact that "modified INAFOGA method" is indeed appropriate under mixed traffic conditions.



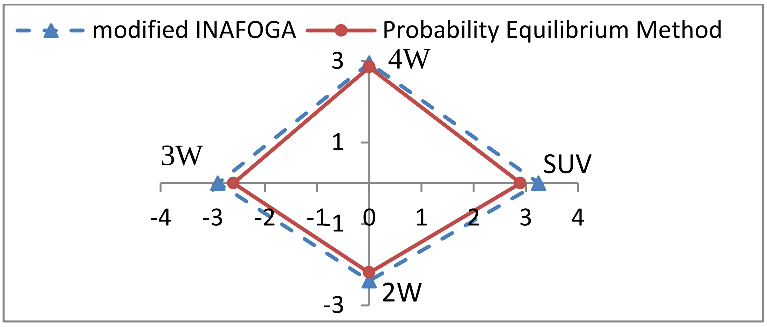
(a) Critical gap comparison for section 1



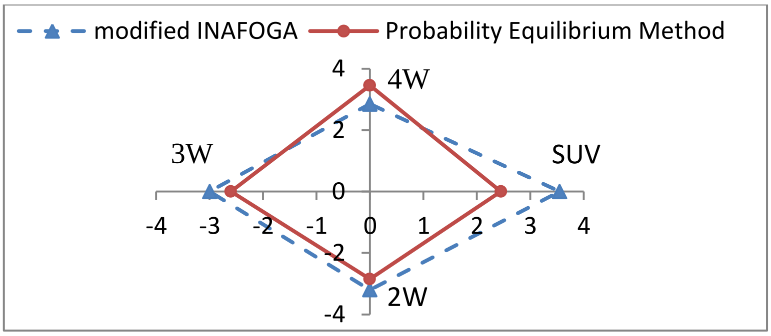
(b) Critical gap comparison for section 2



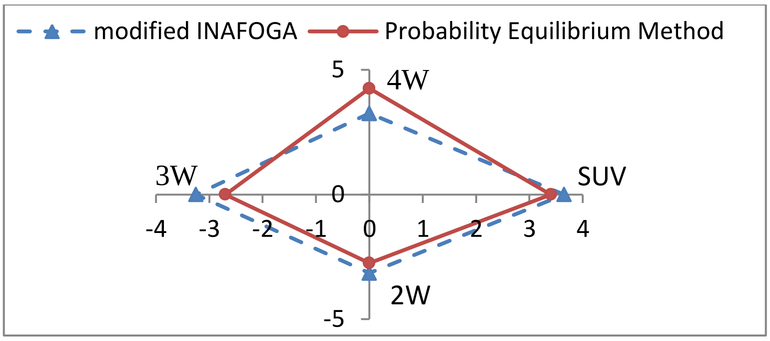
(c) Critical gap comparison for section 3



(d) Critical gap comparison for section 4



(e) Critical gap comparison for section 5



(f) Critical gap comparison for section 6

Fig. 5.7 Comparison of critical gaps estimated for all modes at all sections.

5.3 Estimation of follow up time (t_f)

The time frames chosen during extraction of data with the aid of AVIDEMUX software are as follows:

Follow up time (t_f) = T2-T1

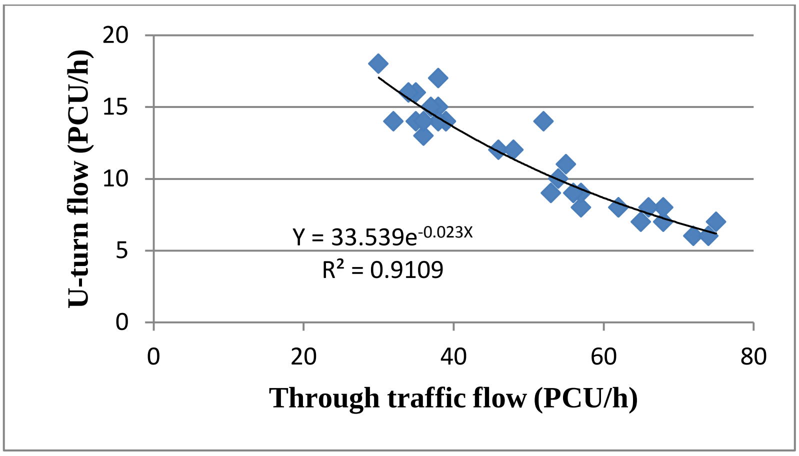
The obtained follow up time (t_f) for section 1, 2, 3, 4, 5 and 6 are 2.24 sec, 2.09 sec, 2.14 sec, 1.78 sec, 1.78 sec and 1.76 sec respectively.

5.4 Estimation of Capacity

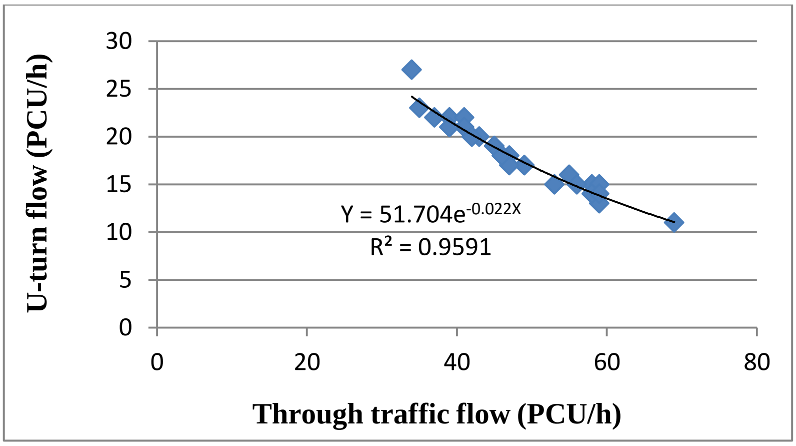
Capacity of U-turn vehicles mainly depends on critical gap and follow up time. In the previous sections to represent mixed traffic conditions, critical gap and follow up time are estimated by mode wise such as 4W, 3W, 2W and SUV's. But for the estimation of capacity, critical gap and follow up time values should be in section wise. Therefore critical gap and follow up time are estimated by mode wise and section wise in this study. Results are shown in the corresponding situations respectively. Fig. 5.8 represents the critical gap (t_c) of U-turn vehicles for section1, 2 and 3. Remaining sections follow the same pattern of plot.

From the above graphs, the obtained critical gap values (t_c) for sections 1, 2, 3, 4, 5 and 6 are 2.8 sec, 3.0 sec, 2.4 sec, 3.0 sec, 4.0 sec and 3.6 sec respectively.

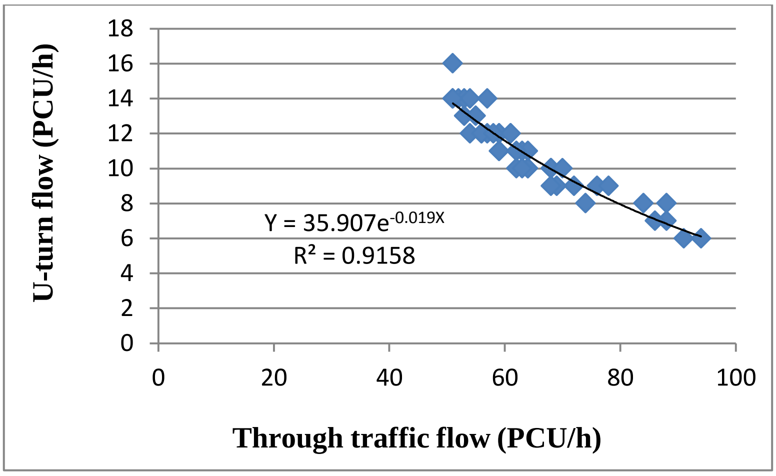
Fig. 5.9 shows the scatter plot of U-turn flow and conflicting traffic flow for all median openings. To represent mixed traffic conditions, data were collected from 4-lane, 6-lane and 8-lane roads of Hyderabad city. Each arterial has a different number of through traffic lanes; and vehicles using these lanes conflict with the U-turning vehicle. Thus, it is more reasonable for capacity estimation of U-turn vehicles as a function of through traffic flow irrespective of the number of through lanes.



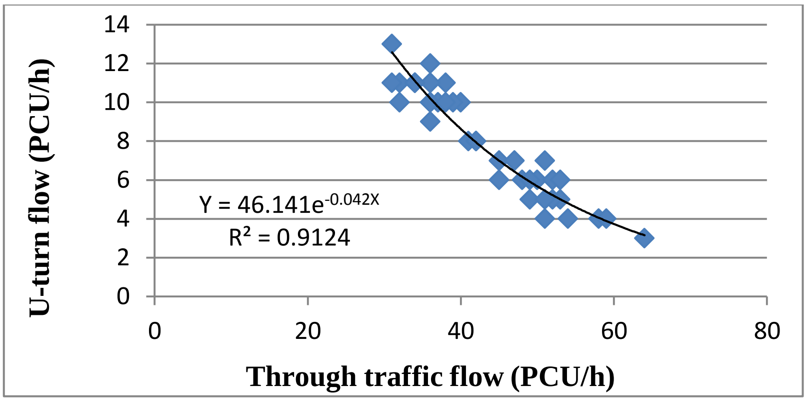
(a): Scatter plot of U-turn flow vs. through traffic flow at section 1



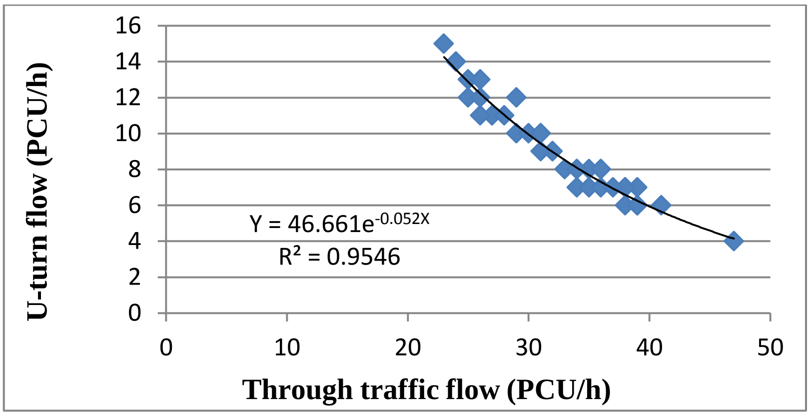
(b): Scatter plot of U-turn flow vs. through traffic flow at section 2



(c): Scatter plot of U-turn flow vs. through traffic flow at section 3



(d): Scatter plot of U-turn flow vs. through traffic flow at section 4



(e): Scatter plot of U-turn flow vs. through traffic flow at section 5

Fig. 5.9 Scatter plot of U-turn flow vs. through traffic flow for all sections

From the above figure all these scatter plots are showing exponential variation with the following equation

Where 'Y' represents the U-turn flow and 'X' represents the through traffic flow and A, B are coefficients.

The above equation represents the siegloch's (1994) capacity model as

$$C = \left(\frac{3600}{t_f}\right) * e^{-p(t_c - (\frac{t_f}{2}))} \tag{2}$$

Where C= capacity of U-turn vehicles

t_c = critical gap

t_c = follow up time

$p = \frac{q}{3600}$

q = through traffic flow

But the above equation (2) considers the homogeneous traffic conditions and over estimates the minor stream capacity even if critical gaps are estimated for local conditions. Therefore to account for mixed traffic conditions, siegloch model is modified and applied for U-turn movements at median openings to develop a new capacity model.

Tables 5.5 represents the estimated critical gap, follow up time and measured traffic flow for through traffic as well as U-turn traffic for all sections along with constants obtained in comparison.

Table 5.5 estimated critical gap, follow up time of U-turn vehicles at median openings

Median opening no.	U-turn flow (PCU/h)	Through traffic flow (PCU/h)	A	B	t_c sec	t_f sec
Section 1	772	2924	33.539	0.023	2.8	2.24
Section 2	985	2865	51.704	0.022	3.0	2.09
Section 3	824	3646	35.907	0.019	2.4	2.14
Section 4	794	2490	46.141	0.042	3	1.78
Section 5	728	1980	46.661	0.052	4	1.78
Section 6	882	3086	-	-	3.6	1.76

Regression analysis is carried out to develop the relationship between coefficient 'B' and t_c, t_f variables. Based on the analysis, the following relationship has been proposed with R^2 value 0.977 at zero regression constant.

Substituting the proposed B in the equation (2) the capacity estimation equation is modified and represented by the following:

The follow up times and critical gaps estimated from this study has been substituted in the above equation (3) and a set of capacity values for five median openings represented by [C_1, C_2,C_3,C_4,C_5] is found to be [1579.68, 1685.66, 1656.51, 1978.77, 1966.98] PCU/h respectively. The observed U-turn flow values for the same median openings are [772, 985, 824, 794, 728] PCU/h respectively shown in the second column of the Table 3. Relationship among these two sets of capacity values is developed through the application of regression analysis and a coefficient of correlation value of 0.457 is obtained. The obtained coefficient used as a multiplying factor in the equation (3); hence the final proposed capacity estimation model for mixed traffic flow conditions is represented as

$$C = \left(\frac{3600}{t_f}\right) * \ e^{-p(t_c-(\frac{t_f}{2}))}$$

Where, C = capacity of U-turn vehicles

t_c = critical gap of U-turn vehicles

t_f = follow up time of U-turn vehicles

$p = \frac{q}{3600}$

q = through traffic flow

5.5 Capacity Model testing

In the present study, data collected from section 6 is used for the capacity model testing. The traffic conditions and roadway characteristics observed in Section 6 are (1) The U-turn median opening is especially designed where there is no substantial disruption from other minor movements. (2) The distance from the upstream signalized intersection to the selected median opening is very high. Therefore, the upstream signal does not affect the appearance of the through traffic. (3) The distance from the downstream signalized intersection to the selected median opening is also very high. Therefore, the traffic from downstream signal does not back into the subject median opening.

In order to estimate the capacity of U-turn vehicles at section 6 the values on the following variables such as critical gap, follow-up time and through traffic flow shown in the Table 3 are utilized.

By substituting the above values in equation 4,

$$C = 0.457 * \left(\frac{3600}{1.76}\right) * \ e^{-\frac{3086}{3600}(0.019757(3.6)-0.01428(1.76))} \quad = 898.63 \text{ PCU/h}$$

This value estimated using the proposed model (equation 4) is close to the field observed value of 882 PCU/h. Hence, the capacity model proposed for the mixed traffic conditions is valid logically.

CHAPTER 6

CONCLUSIONS AND DISCUSSIONS

6.1 Conclusions in General on Estimation of Critical gaps

HCM (2000) suggests the values of critical gap at un-signalized intersections for all priority movements. However, it does not consider mixed traffic situations and values of critical gap are given only for cars. According to this manual, the critical gap value for a car taking U-turn at median opening is 4.10 s. The values of critical gap by modified INAFOGA method are given in Table 5.3 ranges from 2.65 to 3.25 s (average 2.98 s). Results using the merging behavior concept applied in this study are found to be lower by 27% as compared to the value given in HCM (2000). It is assigned to the new definition of gap acceptance and influence area used in the present study. The average critical gap values for 3wheelers, 2 wheelers and SUV's are 2.80 s, 2.58 s and 3.65 s respectively. Table 6.1 represents the comparison of the values of critical gap estimated by the proposed method with the lowest and highest values among the existing methods. The critical gap values estimated by the proposed method are in between than that estimated using existing methods because the new method modified INAFOGA takes into account the merging behavior along with the gap acceptance characteristics. The merging time represents the manner in which a vehicle clears the median opening and is very important under mixed traffic conditions where lane and priority disciplines are absent.

Table 6.1 Critical gap comparison by proposed method and with existing methods

Median Opening Section no	Vehicle type	Critical Gap values of U-turn Vehicles		
		Proposed Method	Existing Methods	
			Lowest	Highest
Section 1	4W	3	2.9	4.25
	3W	2.6	2.5	3.75
	2W	2.5	2.4	3.25
	SUV	3	2.9	4.25

Section 2	4W	2.9	2.65	3.75
	3W	2.7	2	3.75
	2W	2.4	2.4	3.25
	SUV	4.8	3.1	5.25
Section 3	4W	3.2	2.25	3.75
	3W	2.4	1.9	2.9
	2W	1.8	1.5	2.25
	SUV	3.7	2.5	4.25
Section 4	4W	2.95	2.85	4.25
	3W	2.9	2.6	3.75
	2W	2.4	2.2	3.25
	SUV	3.25	2.9	3.25
Section 5	4W	2.85	3.45	4.8
	3W	3	2.6	3.75
	2W	3.2	2.85	4.25
	SUV	3.55	2.45	4.25
Section 6	4W	3.25	4.25	5.75
	3W	3.25	2.7	3.75
	2W	3.15	2.75	4.25
	SUV	3.65	3.4	4.25

The critical gap values estimated by mixed traffic conditions for four types of vehicles at median openings, using two existing methods are available in background of the study. These values are observed to be rather high with significant variation (10%-42%) between the values estimated by the existing methods. This shows the limitations of these existing methods for the measurement of gap acceptance under mixed traffic conditions. In order to address this issue, recently developed method 'INAFOGA' which is based on clearing behavior of drivers at un-signalized intersections is modified and applied in this study by considering the merging behaviour of U-turn vehicles at median openings. It considers the actual merging behavior in addition to the gap acceptance features of a vehicle. Merging time shows the manner in which a movement is implemented at a median opening. It alternatively takes into account the difficulties found under mixed traffic conditions. The estimation of critical gap developed in this paper is easy to implement, simple and suitable to mixed as well as uniform traffic conditions. Thus, the modified concept introduced in this paper will definitely serve as a handy tool for future traffic engineers/ policy makers to improve traffic operations on un-signalized median openings.

6.2 Conclusions in General on Estimation of Follow up time

Queuing conditions are observed in the field hence the follow up time is estimated at median openings and the average value of all sections is found to be 1.96 sec. This value is lower than the value suggested by HCM (2010) due to mixed traffic conditions.

6.3 Conclusions in General on Estimation of Capacity

Table 6.2 represents the comparison of the capacity values estimated by the proposed model with the lowest and highest values among the existing models. The capacity values estimated by the proposed method are higher than the existing models because the vehicular interactions under mixed traffic conditions during the peak hours significantly influence it. Smaller sized vehicles often squeeze through the any available gap between larger sized vehicles and do not follow the lane discipline hence impact the capacity. Other factors such as no proper lane marking, lack of enforcement leads to the wide variation in capacity values proposed by a new model.

Table 6.2 Comparison of capacity values by proposed model and with existing models

Median opening section no	Capacity values of U-turn vehicles		
	Proposed model	Existing models	
		Lowest	Highest
Section 1	720.42	233.29	410.62
Section 2	768.68	206.7	363.46
Section 3	755.50	200.79	437.41
Section 4	902.56	214.07	469.96
Section 5	897.10	148.04	365.61
Section 6	898.32	96.61	198.68

The capacity values estimated under mixed traffic conditions for all sections at median openings, using four existing models are available in background of the study. These values are observed to be rather high with significant variation (43%-59%) between the values estimated by the existing models. This shows the limitations of these existing models for the capacity estimation of U-turn vehicles under mixed traffic conditions. In order to address this issue, a new model is proposed for estimating the capacity of U-turn vehicles at median openings considering mixed traffic conditions. The estimation of capacity model proposed in this paper is simple, easy to implement and suitable to mixed traffic conditions. Thus, the proposed model introduced in this paper will definitely serve as a handy tool for future traffic engineers/ policy makers to improve traffic operations on un-signalized median openings. However, there is little doubt about the utilization of the merging behavior concept to other transportation facilities such as roundabouts, interchanges, etc. and thus further research in this regard is recommended.

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